Prof. John Campbell's Ten Rules for Making Reliable Castings

Mark Jolly

John Campbell's "Casting Rules" were developed over a lifetime of work in the foundry industry and later research at the University of Birmingham. Much of the research work focused on the effect of melt handling at the various transfer stages on the number of defects created and the effect on the reliability of the castings subsequently made. This article provides the author's analysis of Campbell's ten rules for metal casting.

INTRODUCTION

The author first met John Campbell in a pub in the outskirts of Birmingham, United Kingdom, some 20 years ago. Intrigued initially by the fact that Campbell wore a bow tie, eventually he began to hear the truth about castings and the dreadful news that they were all full of defects. And what's more, the way most foundries made castings was making a process with a poor reputation for reliability even worse, and most foundrymen did not even realize it. In the intervening years this message has started to get out into the industry and a band of industrialists and academics has been persuading manufacturers of the truth of John Campbell's arguments. This article is a brief synopsis of the major reasons castings fail, supported by the underlying science. It follows from the conference held in his honor at the 2005 TMS Annual Meeting in San Francisco. Campbell is now retired from the University of Birmingham but still works there most days.

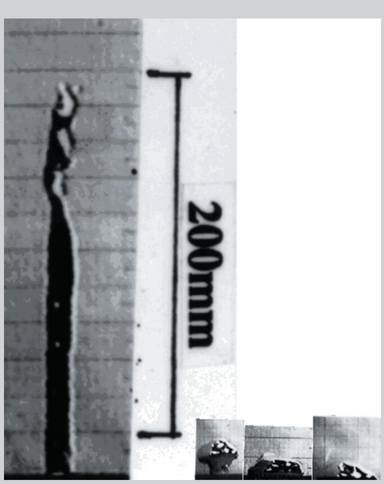


Figure 1. A video capture of in-gate jetting in aluminum for velocities of 3.00 ms^{-1}, 0.75 ms^{-1}, 0.50 ms^{-1}, and 0.21 ms^{-1} from left to right. The metal is traveling up the page.[2]

John Campbell's "Casting Rules"[1] were developed over a lifetime of work in the foundry industry, and later research work at the University of Birmingham. Much of the research has investigated the effect of melt handling at the various transfer stages on the number of defects created and the effect on the reliability of the castings subsequently made.

Runyoro[2] showed the effect of in-gate velocity on the amount of turbulence created. His video recordings of liquid aluminum jetting up are graphic examples of what foundry workers do not usually see inside the casting cavity (Figure 1). Runyoro also produced definitive evidence for the effect of the metal in-gate entry velocity on mechanical properties. Figure 2 shows that at 0.5 ms^{-1} there is a dramatic fall-off in bend strength of aluminum plate castings that is not apparently related to detectable cracks within the castings. Nyahumwa[3] then went on to show that a number of different types of oxide existed and that each type had an individual effect on the fatigue life, which could best be shown by using Weibull statistical plots (Figure 3). Filtering the metal during casting and post-casting hot isostatic pressing improved the casting reliability. These researchers have shown demonstrably and quantitatively the importance of running system design and control of oxides to the integrity of aluminum castings.

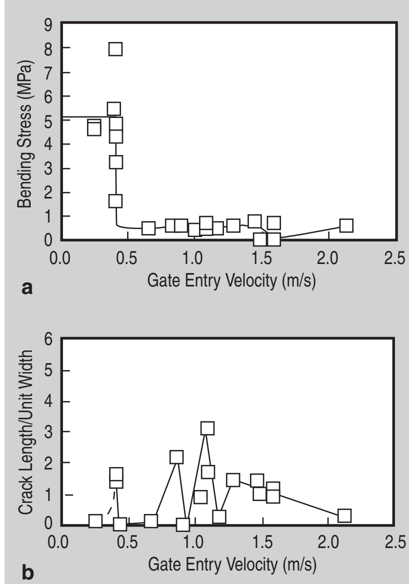


Figure 2. The drop off in properties for aluminum in bend tests when plotted against gate entry velocity and the lack of relationship with detected crack length. (a) Bend strength against gate entry velocity for aluminum. (b) Detected crack lengths against gate entry velocity for aluminum.[3]

LIQUID METAL QUALITY

"Immediately prior to casting the melt should be prepared and treated using the best current practice."

Before making a casting, the liquid metal that is used should be cleaned to the highest level possible. There is no point in developing filling and feeding systems to ensure good quality in the

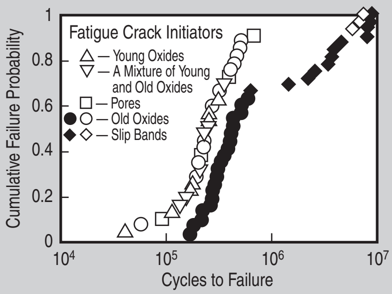


Figure 3. The effect of oxide type on fatigue life.[3]

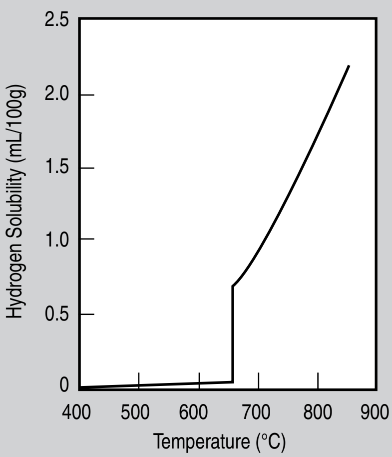


Figure 4. The solubility of hydrogen in aluminum with temperature.

casting if the original material is flawed. High quality means that there should be no, or a low level of, inclusions, and similarly a level of dissolved gas that will not give problems on solidification. The starting point for clean metal is the ingot from which it is manufactured or the cleanliness of the scrap.

In aluminum foundries, the furnace charge could be made up from a mixture of primary ingot, secondary (recycled) ingot, bought-in scrap, and in-house returns from the runners and feeders that have been cut off in the fettling process. It is unusual to start with only ingot but that may be necessary to ensure certain alloy compositions (e.g., for aerospace castings). Recycled aluminum alloy tends to have a higher iron content, which in turn results in higher levels of detrimental iron-containing intermetallics. The two major defects that arise at this stage in the liquid metal are oxides and dissolved hydrogen.

The level of oxide in the ingot will depend on the manufacturing route and supplier. Material that is supplied from continuously cast billet tends to have a lower oxide inclusion level than traditionally pigged ingots (rough open-cast bars that have had no special control during the pouring). It is possible to request material that is certified to a certain level of inclusions, but it is not yet normal foundry practice.

Oxide inclusions can also arise from the scrap that is being remelted if the foundry practice is not of a high enough standard. Other nonmetallic inclusions can arise from furnace refractories, but they are usually bigger than those that are created endogenously.

Hydrogen arises from the reduction of water present in the atmosphere by the reactive aluminum surface. This is shown in the following equation:

$$2Al + 3H_2O = Al_2O_3 + 6H \qquad (1)$$

The hydrogen is then dissolved as nascent hydrogen in the molten alloy.

Figure 4 shows the relative solubility of hydrogen in liquid and solid aluminum and demonstrates why dissolved hydrogen is a problem. Figure 5 shows the effect of high hydrogen levels on casting after heat treatment. The recommended level of hydrogen for good aluminum casting is less than 0.1 cm^3 per 100 g (0.09 ppm by mass), although in aerospace casting it is recommended that levels be lower than 0.05 cm^3 per 100 g (0.045 ppm by mass).

In aluminum alloys, both metal quality and hydrogen levels can be measured using a number of different techniques, as listed in Tables I and II. Molten aluminum quality can be measured directly or destructively from the solidified component. Direct measurement tends to be more expensive, but it is fundamentally more accurate. Unfortunately, not all foundries use measurement techniques.

Hydrogen and nitrogen can also cause problems with porosity in cast irons. Cupola-melted iron is usually saturated with nitrogen. As the carbon content increases, the solubility levels decrease (Table III). Silicon further decreases the solubility of nitrogen. Unlike hydrogen in aluminum, the solubility of nitrogen increases on solidification. The amount by which it increases depends on the carbon content of the first solidifying phase. For hydrogen, the solubility in austenite is about the same as for the eutectic composition of liquid. In this case there is little or no diffusion on solidification. It is usual to remove both hydrogen and nitrogen by inert gas flushing. Steel is similarly affected by hydrogen and nitrogen.

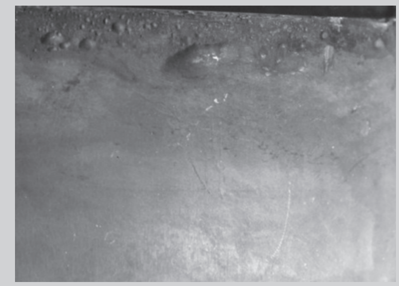


Figure 5. Hydrogen blisters in A356 die casting after heat treatment.

In ferrous alloys, the other source of poor quality is inclusions. These can be endogenous in nature, such as oxides, sulfides, or even nitrides, or complex compounds of all three. They are nearly always detrimental to mechanical properties. Exogenous inclusions usually are a result of the breakdown of containment or mold refractory materials. Exogenous inclusions are generally larger, and as it is now common practice to filter most castings, it is rare to find such inclusions in a well-run foundry. Endogenous inclusions are usually controlled chemically. Oxides can be reduced by deoxidizing with aluminum or silicon; sulfides are controlled by the refining process. It is also usual to ensure that there is enough manganese present to form MnS inclusions, which melt at a lower temperature than FeS. Complex silicates also form as slag on the surface of the melt.

With ductile iron, the use of magnesium to produce the nodularity of the graphite phase creates problems via the formation of complex stable magnesium oxides and silicates. These problems are exacerbated by turbulent filling.

In copper-based alloys, the main quality problem is caused by oxygen, which forms a eutectic with copper with a composition of 0.39 wt.% oxygen. The Cu_2O will produce internal, endogenous oxide inclusions. This can be controlled with the addition of elements that combine to form oxides more easily than copper does, such as lithium, boron, magnesium, and phosphorus. Some copper alloys are also prone to dross formation; an example of this is aluminum bronze, where precautions similar to those for

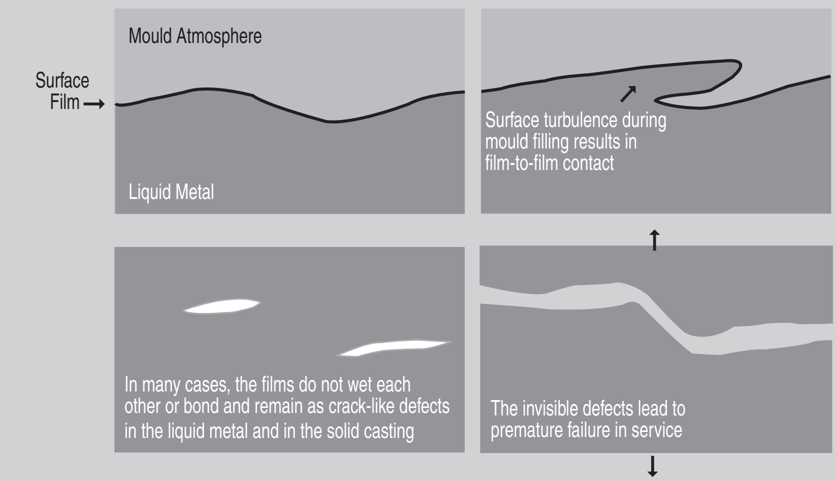


Figure 6. A schematic of the mechanism of surface film damage from turbulence. Original image by R.A. Harding.

aluminum alloys must be taken in running and gating.

SURFACE TURBULENCE (MENISCUS DAMAGE)

"The liquid metal front should not go too fast. Critical meniscus velocity for most liquid engineering alloys is in the range 0.4 to 0.6 ms^{-2}."

Latest research has demonstrated that for every liquid metal there is a critical velocity above which the surface will fold over and entrain itself in the bulk of the metal. It has been postulated that the critical velocity, v_{crit}, can be given by

$$v_{crit} \approx 2\sqrt[4]{\frac{\gamma g}{\rho}} \approx 3.54\sqrt[4]{\frac{\gamma}{\rho}} \qquad (2)$$

where g is the acceleration due to gravity in ms^{-2}, γ is the surface tension in Nm, and ρ is the liquid density in kg/m^{-3}.

For the metallic elements in the periodic table, v_{crit} falls between 0.25 ms^{-1} (Se) and 0.60 ms^{-1} (Be); for the most common engineering materials (i.e., steel, Al, Cu, Mg, Zn, and Ni alloys) it falls between 0.37 ms^{-1} (Zn) and 0.50 ms^{-1} (Ti, Al). Essentially, the critical velocity is directly proportional to the fourth power of the ratio of surface tension to density, so that there is little change throughout the periodic table.

In the majority of casting processes, the metal falls at some stage, either during transfer of liquid metal from one furnace to another or during the pouring of the casting itself. The metal does not have to fall very far to achieve the critical velocity. The velocity, v, of a falling stream can be calculated by

$$v = \sqrt{2gH} \qquad (3)$$

If we assume that the critical velocity is 0.5 ms^{-1} and the acceleration due to gravity is 9.81 ms^{-2}, then the distance, H, in millimeters that the metal has to fall to reach the critical velocity is given by:

$$H = \frac{v^2}{2g} = \frac{0.5^2}{2 \times 9.81} = 12.7$$

This is stating that if the metal falls a distance greater than 12.7 mm, then there will be surface turbulence and the probability of oxide generation, which will then be incorporated into the bulk of the liquid metal.

Runyoro et al.[6] have shown that when the velocity is less than the critical value, then metal entering through an orifice fills a cavity quiescently without surface breaking. This should not be confused with bulk turbulence, because in the majority of casting regimes the Reynolds number is far greater than 2,000, even when there is no surface-breaking turbulence.

More recent work from the research group in Birmingham[7] has indicated that the Weber number is more relevant to whether surface turbulence is going to occur. Bulk turbulence is important once the bubbles have been generated, as the swirling and eddying in the liquid metal can fold up the oxide films into concentrated regions of defect. These will then act as nuclei for shrinkage and dissolved gas evolution during the subsequent solidification processes.

If the critical velocity is exceeded this can lead to folding in of the surface, one of the most detrimental effects that occur during casting. If the liquid surface is covered by a solid oxide film, as is the case for a large number of casting alloys, then the surface film is folded into the bulk of the metal, forming what is essentially a crack in the liquid metal. The mechanism for the formation of these double oxide films is described in the series of schematics in Figure 6. If

Table I. Summary of Metal Quality Tests for Aluminum Alloys

Solid Samples		Liquid Samples	
Name	**Technique**	**Name**	**Technique**
Acoustic	"Wheel tapping" RFDA	PoDFA	Filtration (pressure)
Metallographic	Small laboratory samples	Prefil footprint	Filtration (pressure)
Extraction	Chemical/electrolytic	LAIS/VFT	Filtration (vacuum)
Fast Neutron	Oxygen determination	Density separation	Molten metal centrifuge
Fracture Bar	Mechanical test	LiMCA Coulter method	Electrical
Tool Wear	Historical	Ultrasonic	Reflection of ultrasound

Table II. Summary of Hydrogen Measurement Tests for Aluminum[4]

Reduced Pressure Tests		Fundamental Tests	
Name	**Technique**	**Name**	**Technique**
Straube-Pfeiffer	Fixed pressure	Ransley Probe	Recirculating carrier gas
First Bubble	Variable pressure	Telegas	Development of above
Vibrated Vacuum	Encourage gas bubbles	AlSCAN	Similar to above
Constant Volume	Minimize shrinkage effects	CHAPEL	Direct partial pressure
Density Index	Magnify porosity	NOTORP	Solid-state galvanic cell
Hyscan QRP	Hydrogen from sample	Vacuum solid extraction	Pressure rise
		Nitrogen carrier fusion	Similar to Telegas
		LECO	Remelting test for chilled samples

Table III. Solubility of Nitrogen and Hydrogen in Iron Carbon Alloys at 1,550°C[5]

C (%)	N Solubility (ppm)	H Solubility (ppm)
0	450	24
1	355	21
2	260	17
3	170	14
4	100	11
4.5	65	—

the oxide is liquid at the molten metal temperatures, as is the case for oxides in gray cast iron, then there is a chance that the oxide will globularize and float out back to the surface. The solid oxides form on any alloy containing aluminum, titanium, magnesium, or chromium.

These oxides have been observed with more and more regularity now that the scientific community knows what to look for. Depending on the composition and age of the films, they can range from a few tens of atoms thick to several micrometers. Figure 7 illustrates some oxide films from aluminum alloys.

LIQUID METAL FRONT STOPPING DAMAGE

"At no time during the filling should the liquid metal front stop moving."

If at any time during the filling of the casting the metal front stops moving, the oxide layer has a chance to increase in thickness. If the oxide builds up for too long, then that part of the front may never start moving again, or the metal may just break through in jets. The oxide film then becomes trapped in the bulk of the casting and can often become a through-thickness film. This again is a double film of oxide which behaves like a crack. This happens frequently where large flat castings are filled completely horizontally (Figure 8).

Another example is the so-called waterfall effect. This is where regions of the casting are at a lower level than previously filled parts of the casting, so that molten metal spills into the unfilled regions. The surface of the previously filled part remains static during this phase and is a potential source of problems, as illustrated in Figure 9. It is important, therefore, to ensure that the orientation of the casting considers the full geometry in order to obviate both of these conditions. The objective is to keep the liquid metal front moving in order to ensure that there is a continuous advance of the meniscus at a velocity that is lower than the critical velocity.

BUBBLE DAMAGE

"No bubbles of entrained air should pass through the liquid metal in the mold cavity."

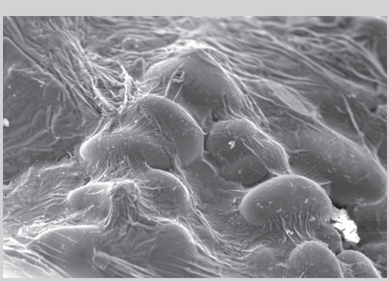


Figure 7. An SEM picture of aluminum oxide film draped over dendrite tips in an A319 alloy (micrograph by G.E. Byczynski).

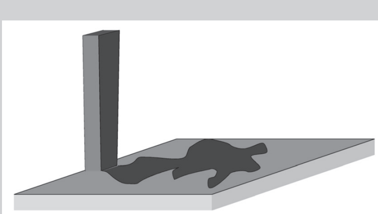


Figure 8. The meandering flow occurring in a horizontal plate casting.

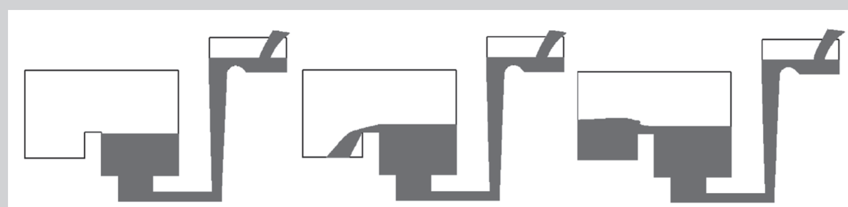


Figure 9. A schematic showing an example of the waterfall effect in filling a casting.

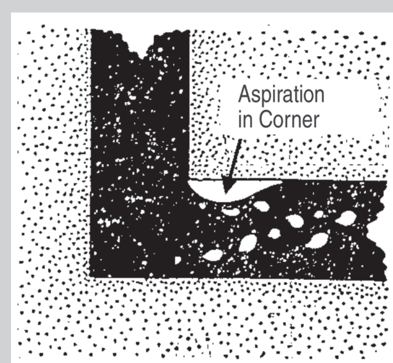


Figure 10. A schematic showing aspiration at a right angle bend especially at the base of the sprue. Metal flow is down and then from right to left.[8]

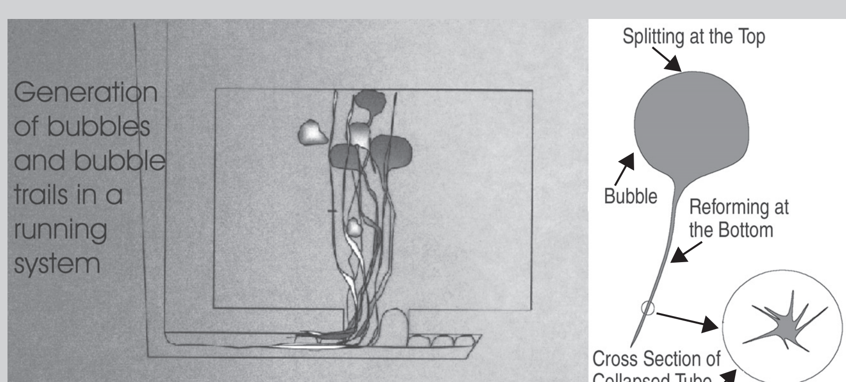


Figure 11. Bubble trail generation, movement, and trail collapse mechanisms in liquid metals.[11]

Bubble damage is probably more widespread than any other form of defect-inducing mechanism in casting. This phenomenon is again associated with surface oxide films, but the mechanism is not one of folding over and surface turbulence as discussed previously. Bubbles can be generated within the liquid metal by a number of mechanisms, but the most common is when the liquid velocity is greater than the critical velocity and there is impingement of metal streams against a surface or other liquid metal. The base of the downsprue (the delivery tube by which the metal travels from the pouring basin to the lowest part of the casting) is a common place for bubbles to be generated, as there is a combination of impingement on the mold surface and the pool of liquid metal in the runner system. Indeed, where there are large volumes of liquid metal with plenty of room for movement (e.g., where the liquid metal is not constrained), there is always the possibility of air entrainment that will create bubbles.

Air can also be entrained in the system anywhere where a low pressure is experienced by the liquid metal. For example, if a downsprue is not tapered correctly, the natural vena contracta of the falling stream of liquid metal will pull the metal surface away from the mold walls and a low-pressure region will be created. If the mold is permeable to air, as is the case in a sand mold or investment shell, then air can be sucked into the falling metal stream, rather in the manner of a venturi pump. Other areas such as the bend at the bottom of the downsprue can also give rise to aspiration, as seen in Figure 10.[8] Hsu has investigated this more recently in Birmingham.[9] Correctly designed downsprues and runner systems can help to avoid bubble generation. Where it is not possible to avoid this, it is important to try to ensure that the bubbles do not enter the casting itself.

Once bubbles have been generated by the turbulence in the system, the story does not end. Bubbles that have been generated from the atmosphere must logically have an oxide surface on the inside. If the oxide is dry and solid at molten-metal temperatures, the bubbles will have a "tail" which emerges to the external atmosphere. It has been postulated[10] that these tails will not heal, and so the bubble is attached to the outside world for the whole of its life. Campbell has also proposed a mechanism of bubble movement through the liquid metal whereby, as the bubble rises through the liquid metal, the top surface oxide breaks and then reforms very quickly from the oxygen inside the bubble. The bubble motion through the liquid produces a trail from its own tail which is anchored at the position of its first entrainment. This tail collapses in on itself and leaves a star-shaped oxide. As more and more bubbles are formed and move through the liquid metal, the oxide trails quickly become a tangled web of oxides, which can in some instances impede the movement of other bubbles through the liquid. When eventually the bubble does reach the surface of the liquid metal and burst, a trail of oxide is left through the metal back to the initiation site. The mechanisms of generation, movement, and bursting are illustrated schematically in Figure 11. Bubble trails have now been identified in many castings and casting processes, and their effect has been reported in a number of publications.[11] Figure 12 shows a scan-

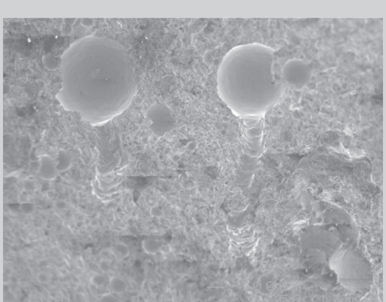


Figure 12. An SEM picture of bubbles and their trails in a die-cast zinc alloy—the largest bubble is about 0.5 mm diameter.[11]

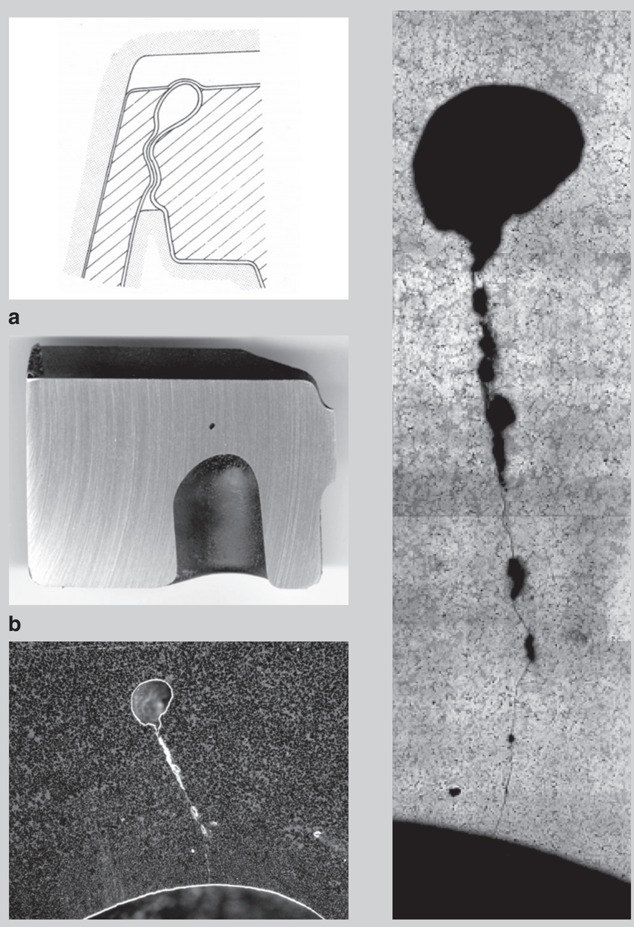


Figure 13. (a) A schematic of core blow from a raised core[13] (b) a macrograph of a core blow in a squeeze casting, and (c) and (d) a macrograph and micrograph showing the bubble trail arising from the core blow with the associated oxide film.

ning electron microscopy (SEM) picture of bubble trails that have been frozen into a high-pressure die-casting.

Bubble trails are probably the biggest cause of lack of pressure tightness in castings, as the trail can provide a leak path from one side of the casting wall to the other. Bubble damage is often misidentified. Many times, having traveled through the casting, the bubble arrives at the solidified outer shell of metal and becomes trapped just below the surface. Such subsurface bubble holes are often diagnosed as mold-metal reaction.

CORE BLOWS

"No bubbles from out-gassing of cores should pass through the liquid metal. Clay-based core or repair materials should be avoided."

Cores are most usually made of sand, although they can be made from glass and even steel. Cores made from sand will be bonded most often with a resin and will be permeable. A number of processes can be used that will produce either solid (hot or cold box) or hollow (Croning or shell) sand cores. There are also some core-repair materials that are water containing. Sand cores thus have a number of sources of gas which can cause so-called "blows" from out-gassing: gaseous reaction products given off by the resin when it comes in contact with the liquid metal—the air inside the natural porosity of the core which expands when the core heats up on contact with the liquid metal, or products containing water which will then expand to give water vapor.

Core blows can be substantially reduced or eliminated by ensuring that cores are dry, especially if they have been repaired or coated, and that they are well vented. This can be achieved by using hollow cores, by drilling vents into solid cores, or by using proprietary venting pipe material. Venting the core is not the only important step, as the gases have to escape from the mold as well. It is therefore necessary to include matching vents in the mold from the core print to the external atmosphere.

Some recent developments in core materials have also been beneficial. Where cores are very long or difficult to drill, venting can be achieved by using high-permeability materials such as "Cerabeads."[12] This has a very uniform grain size, which is almost spherical, and gives a high permeability core (180 cm s^{-1}). The downside is the cost.

Order of filling and precise flow path of the liquid metal can also give rise to blows, especially where confluence occurs over isolated raised areas. Figure 13 is an example of a core blow that was frozen into the liquid metal during a squeeze casting process cycle. Gaseous products from the coating accumulated at the highest tip of the bottom die and formed a bubble which rose through the liquid to produce a blow.

SHRINKAGE DAMAGE

"Uphill feeding should be avoided and feeding requirements should be calculated, not guessed."

Shrinkage in metals occurs during the solidification process as a result of the increase in density that occurs when liquid metals solidify (Figure 14). Theoretically, if there were no nuclei to allow shrinkage to occur at internal sites, all the contraction would be seen on the outside surface. Unfortunately, there are plenty of internal sites for the nucleation of shrinkage, and this internal shrinkage appears as porosity. Oxide films and inclusions are the main ones but there are others, such as refractory particles, grain refiners, and hardeners. In order to achieve a sound casting, a reservoir of liquid metal must be supplied to the casting to feed the requirement created by the change in density. So for a casting to be shrinkage free, the founder often has to supply extra material in the correct place. Foundries have had to cope with this over the years and have developed tools to help achieve sound castings.

Uphill feeding is one process that should be avoided when wanting a casting free from porosity (Figure 15), except when there is no other way to feed a complex casting. Gravity should always be used to aid feeding by the proper positioning of feeders. It is often found that, when castings have poorly placed feeders or atmospheric pressure has not been able to assist in the feeding, the feeders are the soundest part of the metal poured.

For a feeder to be effective, it must solidify later than the casting. Indeed, what is usually attempted is a progression of solidification so that the casting solidifies directionally toward the feeder. To calculate the size of feeder required it is therefore necessary to know how long the casting is going to take to solidify, so that the feeder solidification time is longer. M.C. Flemings[15] proposed that the solution of the partial differential equations for the time of solidification

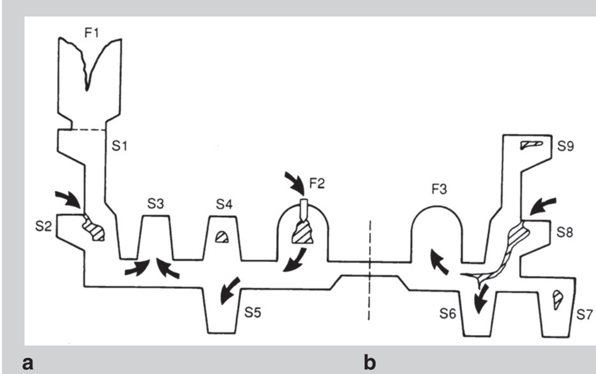


Figure 15. A schematic illustrating uphill feeding. Feeders F1 and F2 are effective because on the (a) side they are using gravity to help feed. Feeder F3 is ineffective as it is trying to feed sections S8 and S9 uphill and the liquid metal's natural tendency is to flow down.[14]

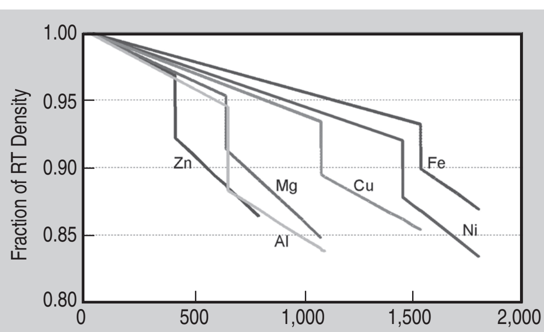


Figure 14. The density changes in metals as they are heated as a function of their room temperature (RT) value.

for a casting can be given by

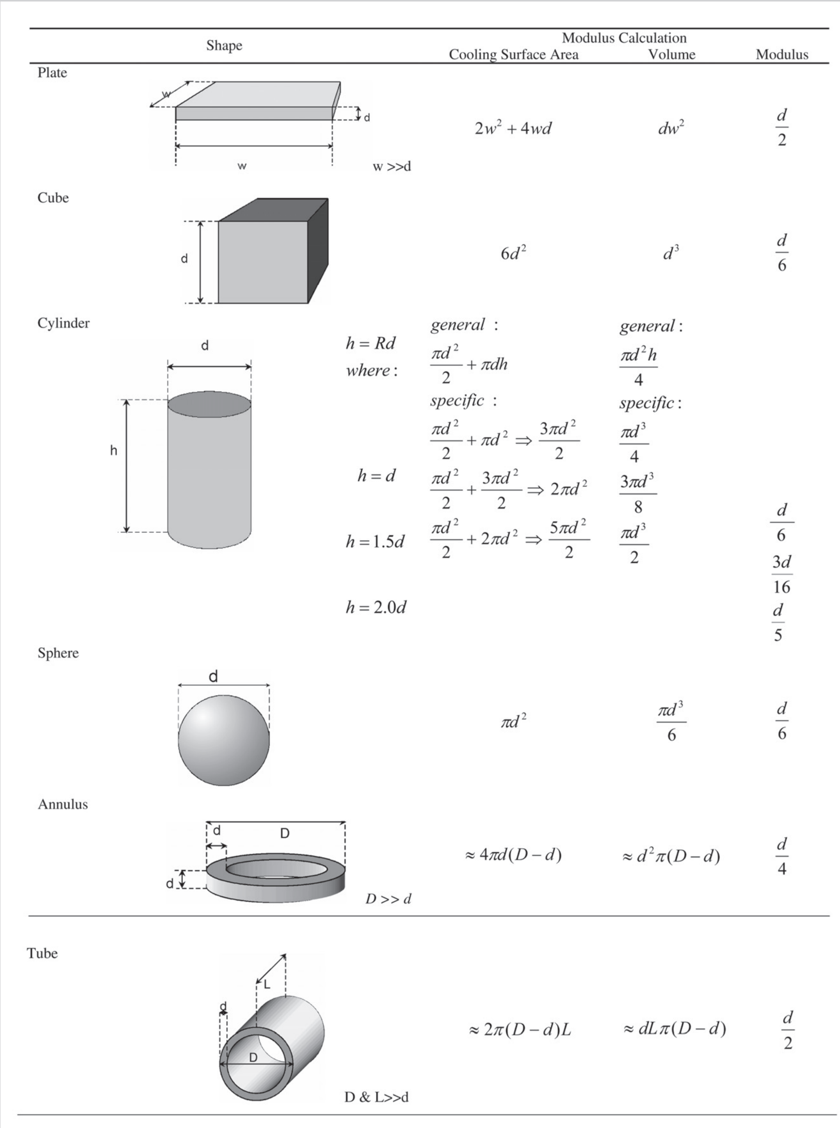
$$S = \frac{2}{\sqrt{\pi}} \underbrace{\left(\frac{T_m - T_o}{\rho_s H} \right)}_{\text{metal}} \underbrace{\sqrt{K_m \rho_m C_m}}_{\text{mold}} \sqrt{t} \quad (4)$$

where T_m is the melting point of the metal, T_o is the initial temperature of an infinite mold, ρ_s is the solid density of the metal, H is the latent heat, and K_m, ρ_m, and C_m are the thermal conductivity, density, and the specific heat of the mold. S is the thickness of solidified metal after any time t.

Founders have been using an empirically based version of this since the early part of the twentieth century that has come to be known as Chvorinov's rule[16] and is encapsulated simply in the following equation:

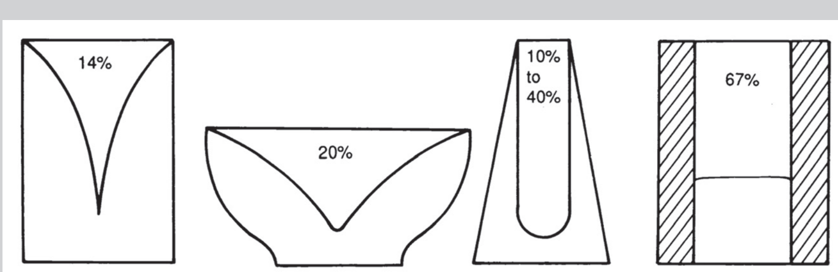
$$t_r = C\left(\frac{V}{A}\right)^2 \quad (5)$$

This equation expresses the fact that the solidification time, t_f, for a casting is related to a constant C and to the square of the ratio of the volume of the casting V to its cooling surface area, A. The ratio of the volume to cooling surface area is known as the modulus, M, and has units of length. The larger a modulus is, the longer the casting will take to solidify. It is common practice to calculate the modulus of the casting (M_c). The feeder



Shape		Modulus Calculation: Cooling Surface Area	Volume	Modulus
Plate	w >>d	$2w^2 + 4wd$	dw^2	$\frac{d}{2}$
Cube		$6d^2$	d^3	$\frac{d}{6}$
Cylinder	$h = Rd$ where:	general: $\frac{\pi d^2}{2} + \pi dh$	general: $\frac{\pi d^2 h}{4}$	
		specific: $\frac{\pi d^2}{2} + \pi d^2 \Rightarrow \frac{3\pi d^2}{2}$	specific: $\frac{\pi d^3}{4}$	
	$h = d$	$\frac{\pi d^2}{2} + \frac{3\pi d^2}{2} \Rightarrow 2\pi d^2$	$\frac{3\pi d^3}{8}$	
	$h = 1.5d$	$\frac{\pi d^2}{2} + 2\pi d^2 \Rightarrow \frac{5\pi d^2}{2}$	$\frac{\pi d^3}{2}$	$\frac{d}{6}$
				$\frac{3d}{16}$
	$h = 2.0d$			$\frac{d}{5}$
Sphere		πd^2	$\frac{\pi d^3}{6}$	$\frac{d}{6}$
Annulus	D >> d	$\approx 4\pi d(D-d)$	$\approx d^2\pi(D-d)$	$\frac{d}{4}$
Tube	D & L>>d	$\approx 2\pi(D-d)L$	$\approx dL\pi(D-d)$	$\frac{d}{2}$

Figure 16. The casting moduli of some primitive three-dimensional shapes.



a b c d

Figure 17. The effect of feeder geometry on the volume of metal available for feeding (a) un-insulated cylinder, (b) hemisphere, (c) truncated cone, and (d) insulated cylinder.[14]

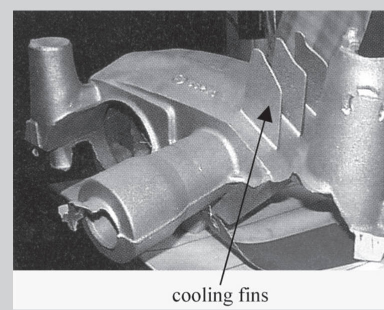


Figure 18. Cooling fins being used in a U.S. aluminum foundry.[19]

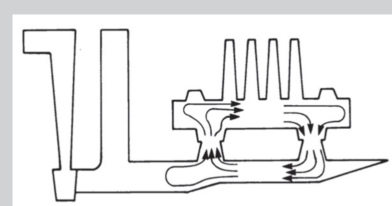


Figure 19. The mechanism for developing convection in bottom-gated castings.[14]

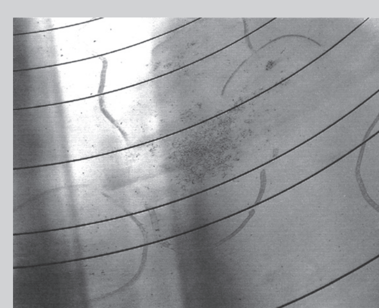


Figure 20. An example of shrinkage created by convection in an aluminum casting marked up by a foundry quality inspector.

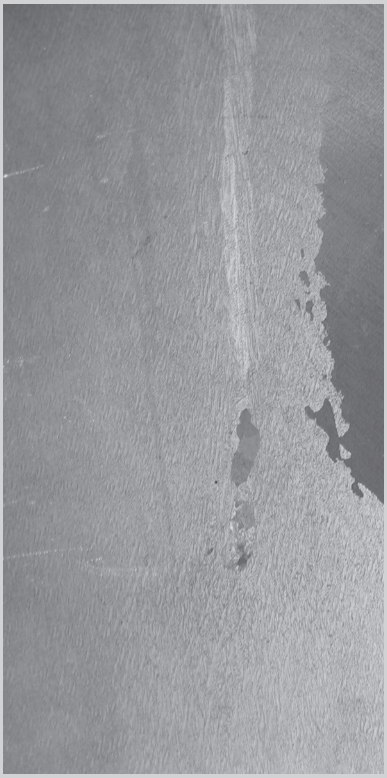


Figure 21. A macrograph showing an example of freckle and stray grain in a nickel-based superalloy (photo by Masood Turan).

can then be calculated by ensuring that it has a larger modulus than the modulus of the casting. In practice, castings are not simple shapes, and so the casting usually has to be split up into many smaller parts and feeders may have to be put on different areas.

The modulus for a number of primitive shapes is given in Figure 16.[14,17] But how much bigger should the modulus of the feeder (M_f) be to ensure that it solidifies later than the casting? It is common to use a figure of 20%; in other words, $M_f = 1.2\,M_c$, and this works in many instances. However, where the casting is thin and plate-like this may not work. This is because the feeder does not only have to stay live while the casting is solidifying, but it must also supply enough liquid metal to satisfy the shrinkage contraction within the casting.

The shape of the feeder also affects how much feed metal it can provide to the casting. Typically, a non-insulated cylindrical feeder will be able to give up only 14% of its volume to feed the casting it is placed on before the shrinkage moves into the casting; this is shown schematically in Figure 17. Thus, an equation can be derived for calculating the maximum volume of the casting that can be fed from a feeder, by knowing the volumetric contraction (S) and the alloy and the shape of the feeder, as shown in the following equation[17]

$$V_{casting} = V_{feeder} \times \left(\frac{V_{shape} - S}{S} \right) \qquad (6)$$

where V_{shape} is the volume of metal available for feeding.

Another way of solving the shrinkage problem is to chill. Chills are lumps of solid metal or graphite placed in strategic regions of the casting where shrinkage has been found (i.e., usually the heavier sections). In essence, chills reduce the modulus of the casting section by increasing the cooling rate in that region. It is also possible to use cast-in chills, usually called cooling fins. Cooling fins are an effective way of chilling a casting as there is intimate contact with the casting metal at all times. The design of cooling fins has been the subject of a number of research papers (e.g., Wen et al.[13] and Wright,[18] both in 1997.) Figure 18 shows the application of cooling fins in a foundry.[19]

CONVECTION DAMAGE

"Damage due to convection problems should be avoided by ensuring thermal gradients act with, rather than against, gravity."

Convection can cause major problems in sections of castings that are medium in cross section. It is now well accepted throughout the industry that for high-quality castings, the ingate should be at the bottom of the component. This essentially means that the casting is filled uphill against gravity, as this gives control over the way the filling occurs. Thus, the hottest metal in the casting is at the bottom and the coldest metal, the first to enter the mold cavity, is at the top. In a thin-section casting where solidification is very rapid—a matter of seconds—this is not an issue, but where the section thickness is large enough to allow natural convection to occur due to the density differences between the hot and colder liquid metal, the sections become very difficult to feed. The result is that apparently random shrinkage occurs that often gets worse when the feeder or gate size is increased in an attempt to encourage more feeding. With very thick castings (e.g., ingots), the time for solidification is long enough for the convection to reverse the temperature gradient completely and thus satisfy the criterion for feeding by having gravity in the same direction as the negative temperature gradient.

The convection currents can be created in a relatively short time, of the order of minutes, so this problem is also affected by the process. Processes with longer solidification times, such as sand and investment casting, are more susceptible than high- and low-pressure die-casting processes. Gravity die casting can be susceptible, especially where sand cores are used, or where large feeder heads are applied to overcome the positive downward temperature gradient. Figure 19 is a schematic for the mechanism of convection. Figure 20 shows an example of convection-induced shrinkage.

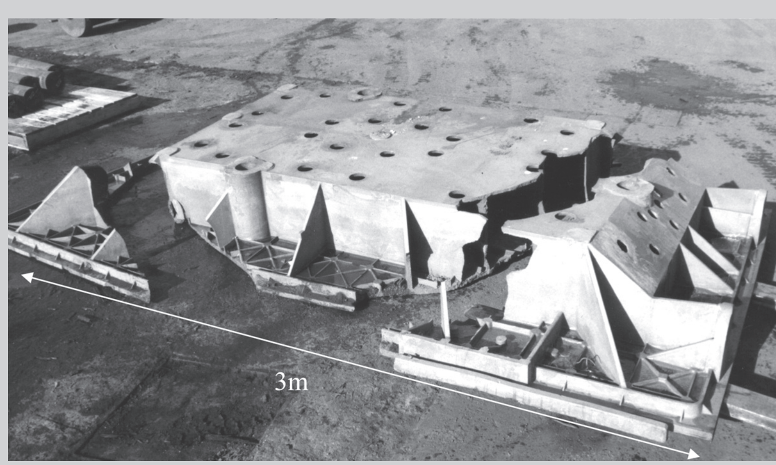


Figure 22. The failure of a casting by quenching in water. The casting was made in A356 aluminum alloy and was over 3 m long.

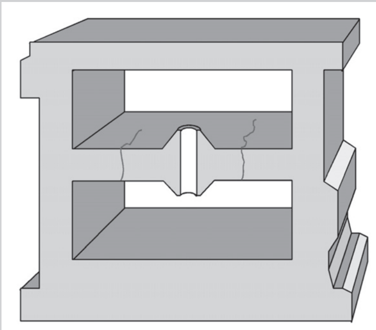


Figure 23. A schematic of residual stresses in a cored casting section giving rise to cracks.

SEGREGATION DAMAGE

"Segregation limits should be agreed with customers and channel segregation must be avoided."

Because modern castings are generally not of a uniform cross section, within a single casting the liquid metal will experience a range of cooling rates. Where the change in cross section is massive, such as at a junction, or where there is a deliberate attempt to alter the cooling rate by chilling or feeding, then it is likely that a change in composition will occur because of what is known as segregation. This can lead to the creation of a pattern of defects similar to the so-called "A" and "V" segregates found in large steel ingots. An example of this is freckle, most commonly found in investment-cast superalloys (Figure 21). This is different from what is commonly called dendritic, micro, or inverse segregation, which occurs as a result of the solute rejection between the dendrite arms.

It is also possible to get buoyancy-driven segregation, where less-dense elements such as carbon, silicon, or even vanadium have segregated to the top of castings, with the concomitant effect of the denser elements, such as tungsten and molybdenum, sinking to the bottom. This is well known in large ferrous castings (e.g., in rolls for rolling mills, which are cast with the axis of the roll in a vertical orientation). This familiar phenomenon, resulting in the "A" and "V" segregation pattern in cast steel ingots, has now been almost completely eliminated by the use of continuous-casting processes. This type of segregation effect produces streams of solute-enriched areas and is more likely to be found in castings where the solidification time is long. Macro-segregation has been addressed by at least one software package[20] in an attempt to to predict macro-compositional changes in large cast ingots.

HEAT-TREATMENT DAMAGE

"Quenching should not be at a rate to produce excessive residual stresses."

After producing a casting to shape, there is nothing worse than seeing it fall apart as it is dunked in water after solution treatment (Figure 22). Quench damage is not only a problem with castings, but can occur regardless of the manufacturing process for any geometry that has a tendency to quench with different cooling rates. The more complex the geometry with regard to changes of section, and the more enclosed spaces there are in the geometry, the more likely that high-tensile residual stresses will be produced on quenching. Internal sections taking longer to cool will initially be loaded compressively. This changes to tensile loading as they contract within the already-cold outer parts (Figure 23).

It is common practice to quench aluminum castings into boiling water in an attempt to alleviate the problem of quench cracking. However, as the solution treatment is usually of the order of 525°C, reducing the temperature drop by 75°C (15%) has little effect. In aluminum alloys, the residual stresses induced by quenching are often above the yield point of the material, and even after subsequent age-hardening processes, the remaining residual stresses can be at a level equivalent to a significant proportion of the yield point. This problem can be solved by quenching in polymer-based quenchants or using forced-air cooling. The aerospace community has recognized this problem and it is usual now to quench aerospace castings in polymer. Some stregth is lost, but the added safety is essential.

MACHINING DAMAGE

"Ensure location points are defined throughout the manufacture of the component, so that at each manufacturing stage, e.g., design, casting, machining, the same datum points are used."

Having made the perfect casting and managed to heat-treat it without its distorting or falling apart, it is frequently necessary to carry out some machining or finishing operations that require the casting to be mechanically handled. Castings are, at times, scrapped at this stage because they will not clean up.

It is essential at the outset of the design of the component that the location points are the same datum points that were used for other phases of the total process (i.e., the pattern maker or tool maker uses the same points to make the tooling as the final machinist will use for the finishing). Many components use a six-point location scheme; the first three points define the first plane, the next two the second plane, and the third defines the last plane (Figure 24). For the best results it is necessary to define all the location points to be in one-half of the mold (in a two-part mold). Datum points should also be as close to the center of a component as possible, rather than at one end. This

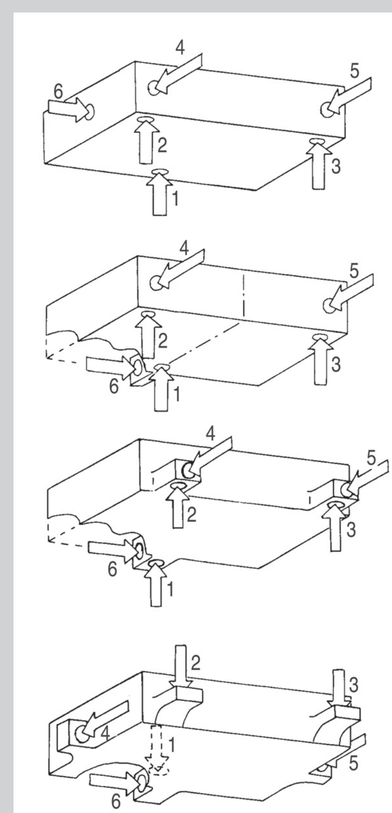


Figure 24. A diagram illustrating potential location point schemes to enable consistent datums throughout manufacture.[17]

helps minimize the variations in length, especially in longer components.

APPLYING THE CAMPBELL RULES

Since the early 1990s, a number of foundries around the world have started to apply the Campbell rules to make better castings. The methods for transferring metal, cleaning, measuring melt quality, and the design of running systems that deliver quiescent metal into the mold cavity are presented in Campbell's books[14,21,22] and summarized by the author in various publications.[23,24] Where the rules have been applied, improvements in the reliability of castings have been substantial.[25] This review is not intended to educate readers in the application of the rules but merely to raise their consciousness to the fact that humankind's oldest metal-working process is finally finding a scientific voice to help its practitioners achieve better results.

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